Defining Cosmological Voids in the Millennium Simulation Using the Parameter-free ZOBOV Algorithm

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Abstract

The Zones Bordering On Voidness (ZOBOV) parameter-free void-finding algorithm is applied to data from the 2005 *N*-body Millennium Simulation. Voids can be used as a distance estimator for cosmic expansion to the first order because they are affected only by dark matter and relatively small quantities of real matter. They are defined by the ZOBOV program as local density minima and their surrounding depressions fixed by Voronoi tessellations. The return from ZOBOV's analysis of the Millennium data depicts the probabilities of voids from Poisson fluctuations instead of assigning parameters to automatically choose a set of voids because there currently is no conventional statistical significance level across void-finding algorithms in astrophysics. Designating a significance level allows for specificity of output voids but overall significance levels vary depending on the goals of the experiment. The voids defined by the ZOBOV program in this paper have a default density threshold of 0.2 so that voids with minimum density greater than 0.2 times the mean density are excluded. Successful results were obtained by running ZOBOV with 58,715 voids found within the full, 9 million particle data set, 6,451 voids found within ~1 million particles, 1,884 voids found within ~300,000 particles, and 483 voids found within ~80,000 particles.

Introduction

The mass distribution of the Universe describes a "cosmic web" which is dominated by filaments that extend from galaxy clusters, sheets of filaments that form complex walls, and under-dense voids that constitute the overall greatest volume (Bond, Kofman, & Pogosyan, 1996). The cold dark matter (CDM) paradigm explains that voids are the result of the foremost local minimum density fluctuations in the Universe. Voids are distinctly defined because they contain significantly fewer galaxies than the corresponding Poisson distribution, or discrete probability distribution, predicts (Rood, 1988). Voids are expanding more quickly than their large-scale (10 Mpc or larger) counterparts, the superclusters. The Universe's expansion and evolution that results in today's distribution of matter is accredited largely to gravitational instability and small fluctuations in density that occurred billions of years ago in the then-homogeneous background (Habib, Feldman, Shandarin, & Heitmann, 2005). Recent cosmic microwave background (CMB) data suggests that the primordial density fluctuations were a Gaussian random field and supernova distance measurements suggest that the majority of the Universe's current energy density is a form of dark energy (Springel et al., 2005).

The evolution of voids is hierarchical and their shape is primarily influenced by tidal fields such that voids do not grow increasingly spherical (Icke, 1984), but tend to exhibit the flattened axis ratios of $c : b : a \approx 0.5 : 0.7 : 1$ (Platen, van de Weygaert, & Jones, 2007). Rather than becoming spherical with time, voids can collide with one another and the result is an irregular shape. Though the gas particles within voids are subject to both the effects of hydrodynamics (shock effects from collisions) and gravitational forces, the complementary dark matter particles are under the weighty influence of gravity alone (Springel et al., 2005). Icke's findings in 1984 described the expansion process over time as gravitational pull from the tidal field that drive the evolution of voids as they grow progressively less dense, while denser areas such as galaxy clusters accumulate more mass. As the voids become growingly under-dense, the sheets of filaments separating them are stretched thin to the point of singular filaments until the collision of two voids (Bond et al., 1996). Voids in smoothed sample distributions represent local density minima and are often well defined by surrounding galaxies.

Observing the evolution of voids requires large-scale simulations in accordance with the ΛCDM model, where Λ represents the cosmological constant for dark energy which accounts for the acceleration of the Universe. Using density fields generated by N-body simulations, properties of voids and those of the galaxies they contain can be studied in detail and relatively parameter-free. Due to the hydrodynamic-free nature of dominant mass component- dark matter particles- the collisionless particles are represented in N-body systems as a set of discrete point particles (Springel et al., 2005). The Virgo Consortium's Millennium Simulation follows $N \approx 10$ billion particles from redshift $z = 127$ to the present ($1 + z$ being the expansion factor of the Universe relative to the present), comprising a cube with edges of $500h^{-1}$ (where h is Hubble's constant in units of $100\text{km s}^{-1}\text{ Mpc}^{-1}$), or roughly 2 billion light years (Springel et al., 2005). The Millennium Simulation represents the largest simulation of the evolution of dark matter structure and is consistent with the ΛCDM cosmology model.

Void-finding algorithms are based on either dark matter density fields or halo/galaxy distributions. The void identification methods vary from connecting under-dense density grid cells to defining empty regions in galaxy distribution and tidal instabilities in smoothed density fields (Colberg et al., 2008). A point of agreement among all current void-finding algorithms is on their voids' distinctly under-dense centers, which fall to less than 10 percent of the Universe's mean cosmic density (Patiri, Prada, Holtzman, Klypin, & Betancort-Rijo, 2006). ZOnes Bordering On Voidness (ZOBOV) is a void-finding algorithm developed by Neyrinck based off of his earlier algorithm, and ZOBOV's counterpart: VOBOZ (VOronoi Bound Zones), a nearly parameter-free halo-finding algorithm which detects density maxima in dark matter *N*-body simulations (2008). The ZOBOV algorithm is altogether parameter-free and detects density minima as well as depressions surrounding the points (Neyrinck, 2008).

Methods

The Virgo Consortium's ΛCDM Millennium Simulation provided the data for analysis. A smaller cube sample was extracted from the complete $500h^{-1}$-edged cube of approximately 9 million particles; the void-finding algorithm was applied to data sets of more than 9 million points (m_total), 1/8 of the entire data set (m_2), 1/27 of the entire data set (m_3), and 1/125 of the entire data set (m_5). The simulation box depicted in Figure 1 at z=0 provides an intricate preview of the cosmic web's filaments, clusters, and voids.

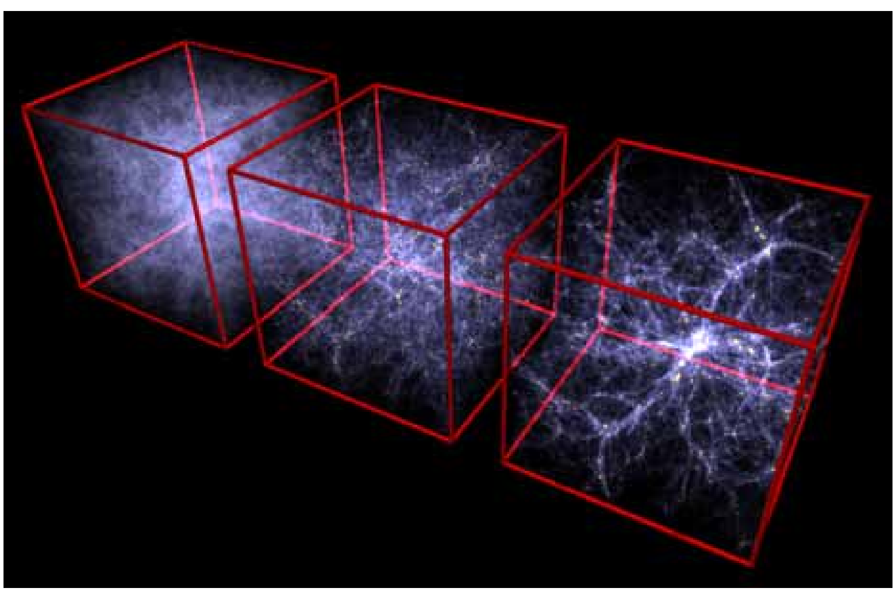

Figure 1. Gaseous formation of structure in the Universe at different redshifts. Left to right: z=6, z=2, z=0. The simulation box is$100h^{-1}$ per edge. From "Cosmic Structure viewed in 3D" by Volker Springel.

The information extracted from the Millennium Simulation's galaxy catalogue included the position (x, y, z) and magnitudes in 5 bands in accordance with the SDSS 'ugriz' system, where colors are a result of simulated galaxy and star formation. The u_mag corresponds to the ultraviolet band, the g_mag corresponds to the green band, and the r_mag, i_mag, and z_band all correspond to varying degrees of red bands. The cosmological parameters on the cold dark matter simulation were:

$$\Omega_m = \Omega_{dm} + \Omega_b = 0.25; \Omega_b = 0.045, \Omega_\Lambda = 0.75, h = 0.73, , n = 1, \sigma_8 = 0.9$$

where Ω_m is the total matter density, Ω_b is the present-day density of baryons, and Ω_Λ is the present-day density of dark energy. The Hubble constant, *h*, has the parameters $H_0 = 100$ h km $s^{-1}Mpc^{-1}$, while σ_8 is the *rms* linear mass fluctuation in a sphere of radius 8 h^{-1} Mpc extrapolated to z=0.

The ZOBOV code consists of two distinct programs: the first set performs a Voronoi tessellation on the input simulation particles—vozinit, voz1b1, and voztie—and the second—jovoz—groups cells returned from the computed Voronoi diagram into voids. All points included in a given Voronoi cell are nearest neighbors of the denoted point, and the vertices of Voronoi diagrams are points that are located maximally distant from all other points in the set. In Figure 2, the displayed Voronoi cells are outlined by edges which contain all points equidistant from two nearest neighbors.

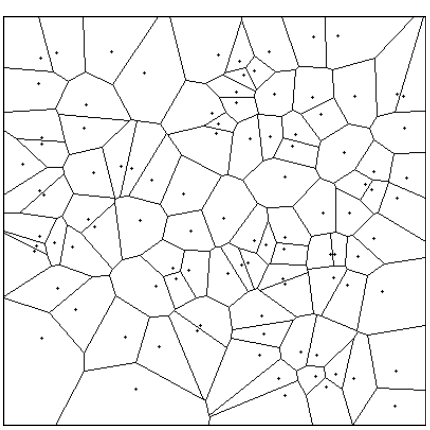

Figure 2. Voronoi diagram displaying a given set of points, surrounding cells (nearest neighbors) and vertices. From http://sense.net/~egan/hpgcc/pics/voronoi.gif.

The first set of ZOBOV's programs (vozinit, voz1b1, and voztie) determines the Voronoi diagram for the input particles, returning for each of the input particles the volume of its Voronoi cell and the set of its adjacent Voronoi cells. ZOBOV's second program joins the Voronoi zones into voids based off of a basin-filling technique. The watershed algorithm requires a topographically diverse data set and acts as though a 2-D plane of the particles were being filled with water. This process is executed for each zone and the "water level" begins at the established minimum density value for that zone, rising gradually and eventually flowing over into other voids. When "water" does flow from its original zone into others, then those zones are added to the void of which the initial zone is a part. If this original zone has the lowest density minimum of all the zones in the data set, then the "water" will continue to flow into new zones and the encompassing void will expand until all of the zones are defined and included. Otherwise the algorithm will terminate when the "water" flows into a zone with a density minimum lower than that of the original zone, and excludes this zone when defining the edges of the given void. The voids defined in the Millennium Simulation cube have a default density threshold of 0.2—which the "water level" does not exceed—so that voids with minimum density greater than the threshold are excluded from the program's output values. In the case of zones with densities that exceed the designated threshold value, the "water" circumvents the zone entirely and excludes it from the list of voids returned.

The data from the Millennium Simulation was obtained in an .ascii format and a FORTRAN program was written in order to convert the data file to 4-bit FORTRAN, or single-precision for ZOBOV's initial program, vozinit. The voz1b1 step requires input parameters for buffer size, box size, and number of divisions. The final values that ran successfully for each of the parameters were : buffer size of 0.13, box size of 245 for m_total, 125 for m_2, 85 for m_3, and 50 for m_5, and the number of divisions were 2 for m_5 and m_3, 3 for m_2, and 4 for m_total. Precise input parameters were essential to prevent errors regarding incorrect numbers of guard points on the surface of the cube.

The three outputs from the completion of running ZOBOV are a text file comprised of 11 columns, a zone membership file describing each of the particles within every zone, and a void membership file detailing the zones contained in each void. Partiview, a visualization interface which allows the user to interact with the data in 3-D space, is able to display particles from the Millennium Simulation sample as well as the voids designated within them.

Results

Parameter	Description
Void#	The rank of the void in decreasing order of VoidDensContrast.
FileVoid#	The number of this void in the first two files.
CoreParticle	The particle number of the void's core particle.
CoreDens	The density, in units of the mean, of the void's core particle.
ZoneVol	The volume of the central zone of the void, in units of the volume occupied by a mean-density particle.
Zone#Part	The number of particles in the central zone of the void.
Void#Zones	The number of zones in the void.
VoidVol	The volume of the void, in units of the volume occupied by a mean-density particle.
Void#Part	The number of particles in the void.
VoidDensContrast	The ratio between the critical density at which water in that zone would flow into a deeper zone to the minimum density.
VoidProb	The probability that that DensContrast would arise from Poisson noise.

Table 1. The key for the ZOBOV output's text file column headers. Descriptions obtained from ZOBOV's Version 1.0 Documentation (Neyrinck, 2008).

Void#	FileVoid#	CoreParticle	CoreDens	ZoneVol	Zone#Part	Void#Zones	VoidVol	Void#Part	VoidDensContrast	VoidProb
1	29919	4798782	3.424102E-02	1.716526E+03	1217	58715	9.509907E+06	9469726	19200956	0.00E+00
2	27341	4367751	3.742695E-02	1.963490E+03	1093	258	6.975150E+04	59076	5.876111	6.55E-41
3	20495	3266794	3.644800E-02	2.629057E+03	1280	10849	3.292183E+06	2573055	5.826913	5.58E-40
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58713	23343	3720575	2.598579E-01	6.88E+01	119	1	6.879818E+01	119	1.000007	1.00E+00
58714	54721	8864631	1.905598E-01	3.068449E+01	18	1	3.07E+01	18	1.000005	1.00E+00
58715	5502	866451	2.060182E-01	1.295497E+02	208	1	1.295497E+02	208	1.000001	1.00E+00

Table 2. Excerpt from ZOBOV output text file for m_total, the full data set. Total of 9469726 particles used.

Void#	FileVoid#	CoreParticle	CoreDens	ZoneVol	Zone#Part	Void#Zones	VoidVol	Void#Part	VoidDensContrast	VoidProb
1	3182	557993	2.482420E-02	3.175813E+03	1656	6451	1.155927E+06	1155928	16405492	0.00E+00
2	4183	738451	7.567468E-02	5.200176E+02	832	3	6.648262E+02	1037	4.533265	1.73E-20
3	5563	989503	2.701133E-02	3.533881E+03	2221	25	2.102731E+04	13854	4.487766	5.79E-20
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6449	2983	516922	5.830915E-01	2.79E+01	56	1	2.790670E+01	56	1.000072	1.00E+00
6450	3232	564918	1.270307E-01	4.405436E+02	276	1	4.41E+02	276	1.000027	1.00E+00
6451	2871	495935	3.007160E-01	3.506454e+01	42	1	3.51E+01	42	1.000021	1.00E+00

Table 3. Excerpt from ZOBOV output text file for m_2, which utilized 2^3 sub-boxes (1/8 the entire data sample was used). Total of 1155928 particles used.

Void#	FileVoid#	CoreParticle	CoreDens	ZoneVol	Zone#Part	Void#Zones	VoidVol	Void#Part	VoidDensContrast	VoidProb
1	9	632	5.715307E-02	7.204807E+02	449	1884	3.063262E+05	306233	4932957	0.00E+00
2	1289	208774	6.064669E-02	8.269384E+02	951	22	6.372504E+03	7140	4.641828	8.77E-22
3	554	89288	5.951446E-02	5.176141E+02	249	143	4.408794E+04	35267	3.586029	1.91E-11
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1882	297	51251	3.036835E-01	6.37E+00	5	1	6.369395E+00	5	1.000678	9.97E-01
1883	1294	209140	1.935214E-01	8.450223E+01	62	1	8.450223E+01	62	1.000214	9.99E-01
1884	264	44422	2.215533E-01	9.804969E+01	118	1	9.804969E+01	118	1.000159	9.99E-01

Table 4. Excerpt from ZOBOV output text file for m_3, which utilized 3^3 sub-boxes (1/27 the entire data sample was used). Total of 306233 particles used.

Void#	FileVoid#	CoreParticle	CoreDens	ZoneVol	Zone#Part	Void#Zones	VoidVol	Void#Part	VoidDensContrast	VoidProb
1	276	46871	5.840478E-02	3.705164E+02	315	483	7.895646E+04	77236	822441.1875	0.00E+00
2	249	41534	6.352914E-02	7.119426E+02	853	28	6.681332E+03	5615	3.233882	5.43E-09
3	431	69169	7.996888E-02	6.068978E+02	397	15	3.047017E+03	2277	2.912571	4.09E-07
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481	420	66748	2.497948E-01	3.24E+01	29	1	3.237182E+01	29	1.001189	9.94E-01
482	190	33564	3.923917E-01	1.469016E+01	16	1	1.469016E+01	16	1.000579	9.97E-01
483	148	28923	1.920005E-01	1.192898E+02	119	1	1.192898E+02	119	1.000577	9.97E-01

Table 5. Excerpt from ZOBOV output text file for m_5, which utilized 5^3 sub-boxes (1/125 the entire data sample was used). Using 77236 particles, 483 voids were found.

Discussion

The void-finding results from four stepwise runs displayed values for number of voids in the Millennium Simulation. The cleanest significant data that was produced with no warning of errors in the program is represented in the m_2 run (1/8 the entire data set, 1155928 particles with 6451 voids found), while the three other runs, though completed, encountered difficulties in the form of warnings concerning messy adjacencies between several zones in the data. The m_total run found 58,715 voids, the m_3 run found 1,884 voids, and the m_5 run found 483 voids. A number of errors experienced while working with the ZOBOV program occurred at each step of the process, but the variation achieved by adjusting input parameters may improve efficiency and productivity of runs during future projects. Void overcounting at the borders of the Voronoi tessellation is one of the greatest sources of error and is a direct result of the open-ended cells that would be established at the edges of a data set.

When observed on a larger scale (observed as even greater than $30h^{-1}$Mpc), voids exhibit tendencies to align in space with the tidal force field and one another (Platen, van de Weygaert, & Jones, 2007). Improved void-finding techniques in the future may allow for further details on the nature of these alignments and, subsequently, the influence of the tidal field on the evolution and development of the cosmic web. For astrophysicists that address the void-alignment question, an important factor for significant results will be the number of voids required to avoid large, systematic errors in using voids as distance indicators.

In the future, voids may be utilized as a distance expansion technique because of their under-dense properties and characteristic size. Though scientists do not know how far away given voids are from Earth, the distance can be calculated because the known factors include the Doppler shift of foreground galaxy to background, the speed of light and Hubble constant, and the redshifts of foreground and background galaxies. Assumed sphericity of voids allows for the angular momentum to be calculated and distances to be measured. By using these known variables, the distance may be calculated.

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